

A Staged Pathway to the Energy Frontier

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In the following we describe a vision for the long-term national high energy physics program that takes the U.S. back to the energy frontier. The vision is muon-based, ultimately leading to a multi-TeV muon collider.

1. Working Assumptions

In constructing a vision for the future of the domestic U.S. accelerator-based high energy physics program, it seems reasonable to assume that, as the only national laboratory dedicated to high energy physics, Fermilab must play a central role. In the following we state our additional assumptions about the near-term program, and about longer-term needs.

1.1 Near-Term Assumptions

- i) In the next few years, getting the ILC built on a “fast track” will be pursued as a high priority, and SCRF R&D will be well supported.
- ii) The fate of the ILC will not be known until 2010-2012 or later, contingent upon LHC physics results.
- iii) There is at least a 10 year gap between the end of the Tevatron Collider running and the beginning of ILC running.

- iv) During this 10 year gap, the U.S. will fully participate in the LHC and its upgrades, and construct the NOvA experiment and its upgrade(s).

1.2 Longer-Term Assumptions

- i) New technologies and approaches are required that will span many years in development, but must be embraced.
- ii) A healthy program must exist along the way to attract students into the field and maintain a diverse population of scientific users.
- iii) We must be willing to shoulder large costs, but ones that are reasonably distributed over time and are matched to the discovery potential of the overall program.

2. A Three-Stage Vision

In the near-term, the timescales for ILC critical decisions and the start of construction are poorly known. It is desirable that a long-term vision for the domestic high-energy physics program be robust against these uncertainties. The staged approach we employ to overcome these uncertainties is shown in Fig. 1.

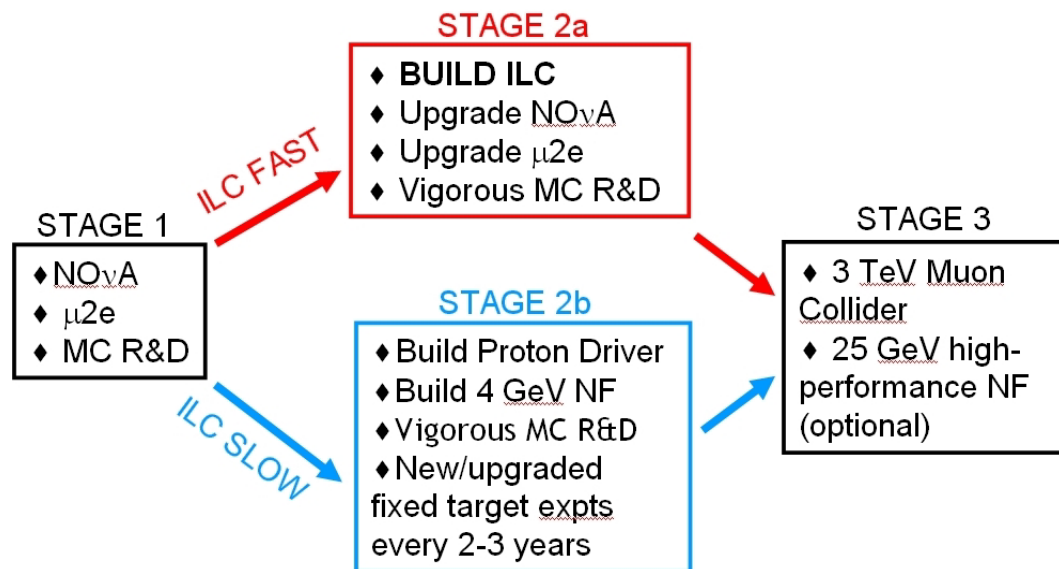


Figure 1: The path to a multi-TeV Muon Collider, in 3 stages.

In our vision, Stage 1 requires no major accelerator construction, and is designed to make sense independent of the ultimate fate of the ILC. If the uncertainty in the ILC timeline continues beyond a few years, Stage 1 extends to keep the program moving in the desired long-term direction, while still not requiring a major new facility. Stage 1 ends with either (i) Stage 2a when we know that ILC is on the fast track, or (ii) Stage 2b if, after about a decade of continued uncertainty, ILC is still not on the fast track. In both Stages 2a and 2b there is a vigorous Muon Collider R&D program that leads ultimately to Stage 3, a multi-TeV Muon Collider.

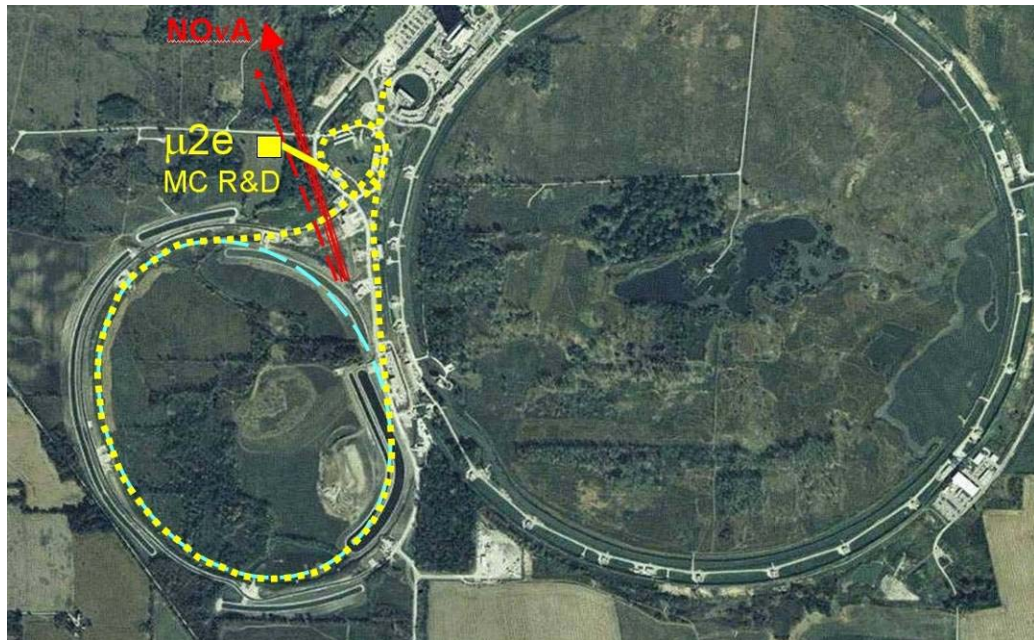


Figure 2: The main elements of Stage 1. The yellow dotted lines show the path 8 GeV protons would take to support a low energy muon program. This would be compatible with simultaneous NOvA running.

2.1 Stage 1

The main elements of Stage 1 (see Fig. 2) are the NOvA experiment, a low energy muon experiment (the example given is a muon to electron conversion experiment: $\mu 2e$), and a healthy Muon Collider

R&D program. The experiments fit within a programmatic theme: The physics of lepton flavor violation. Note that Stage 1 begins a low energy muon program that can be developed in parallel with muon collider R&D and, in the 2b scenario, in parallel with a major intermediate muon-based step towards a muon collider.

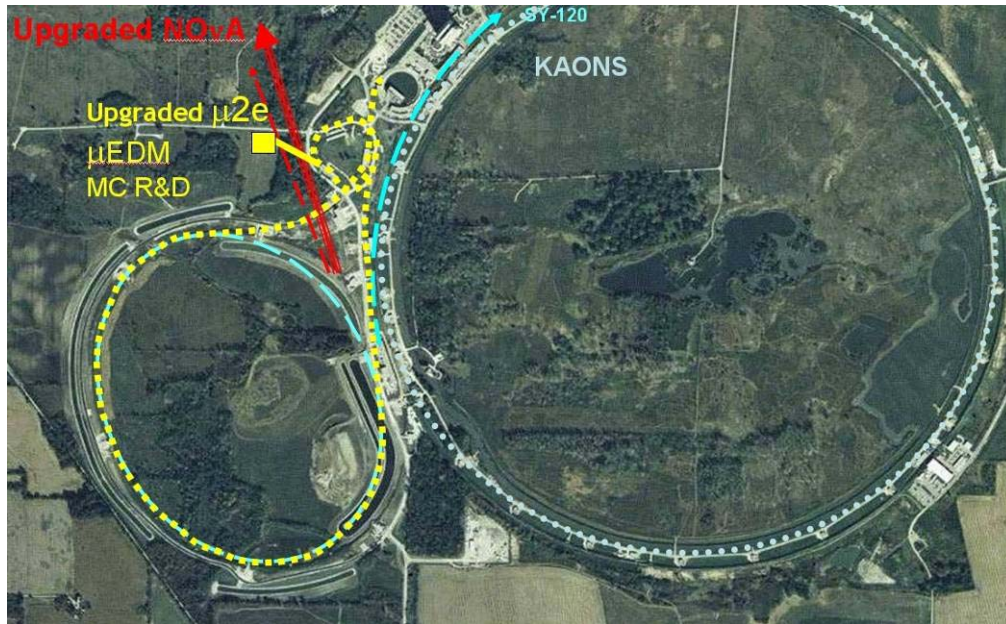


Figure 3: Extended Stage 1 Experiments.

If the ILC timescale remains uncertain, Stage 1 can be extended to include additional world-class cutting edge experiments. Candidates, shown in Fig. 3, include an upgraded NOvA experiment, an upgraded mu2e experiment, a muon electric dipole moment experiment, and a kaon experiment. In this scheme, construction for a new experiment would be started once every couple of years, maintaining a healthy and diverse program that continues to attract students and deliver science.

Estimates for the rough budgets required to support construction of the Stage 1 and, if required, extended Stage 1 experiments, are shown in Table 1. The numbers, which are in units of M\$, are not based on detailed proposals, and are therefore not defensible in any detail. Note that, in constructing our vision, we were not bound by any “budget

guidance”. The budget profile shown should be considered as output from the vision, rather than input that constrains the program. During the 8 year Stage 1 and extended Stage 1 period, the estimated annual funding to construct new experiments ramps up from 20M\$ to 110M\$ (including 10M\$ per year for muon collider R&D). Year 1 in this picture would not be before 2010.

Table 1: Very rough fully-loaded budgets (M\$) required to support the construction of Stage 1 and Extended Stage 1 experiments. The construction of NOvA is assumed to have been completed (or nearly completed) before year 1 of the plan, and is therefore not listed. The time-order of the experiments in the extended program is arbitrary.

		MC R&D	Expt 1	Expt 2	Expt 3	Expt 4
Candidate Expt ?			μ2e	Kaon	μEDM	NoVA Upgr
YEAR	Sub Tot		100	100	100	200
1	20	10	10			
2	50	10	40			
3	60	10	40	10		
4	70	10	10	40	10	
5	80	10	Running	30	40	
6	90	10	Running	20	30	30
7	100	10	Running	Running	20	70
8	110	10	Running	Running	Running	100

EXTENDED PROGRAM

2.2 Stage 2a

The main element of Stage 2a is the construction of the ILC. During the construction period, to fully exploit the investment in Stage 1 experiments, and to maintain a program that continues to attract students and deliver science, the the NOvA and $\mu 2e$ experiments would be upgraded. In addition a vigorous muon collider R&D program would be supported to prepare the way for Stage 3. Hence, a large part of the extended Stage 1 program would be preserved, although the timescales to construct the upgraded experiments would

presumably be stretched out to fit within a reasonable funding profile. Note that even in the “Fast ILC” scenario we believe that a healthy domestic program will require a reasonable level of construction funds, perhaps O(50M\$) per year. Hence, in the Stage 2a scenario an extension of the Stage 1 program would continue, but would ramp up to about 50M\$ per year rather than 110M\$ per year (construction funds only).

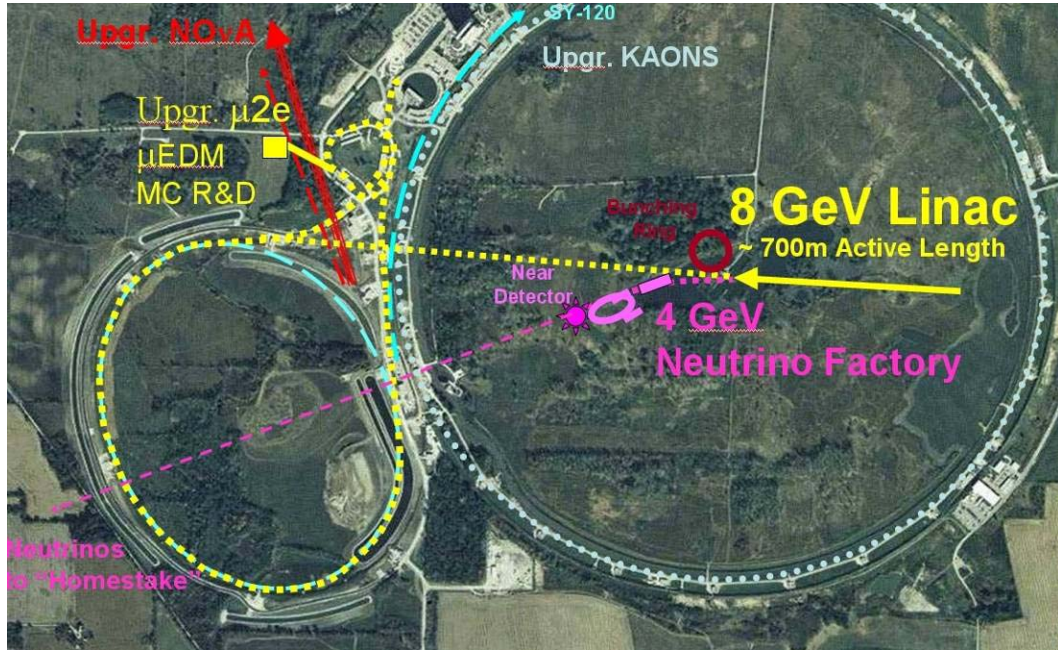


Figure 4: Stage 2b facilities and experiments. The enhanced proton source is taken to be a 700m long SCRF H^- linac. The neutrino factory points towards Homestake in this example, but might equally well point at any far site located at a baseline of 1000-2000km.

2.3 Stage 2b

The main elements of Stage 2b (Fig. 4) are a new 8 GeV proton source providing a 2 MW beam, and a low energy (e.g. 4 GeV) neutrino factory pointed towards an experiment located at a baseline of 1000-2000 km. This represents a significant upgrade of the Fermilab facilities, and is a major step towards a muon collider. The neutrino factory requires, in addition to the proton source, a rebunching ring to produce short proton bunches, target station, pion collection and decay channel, and a muon bunching and phase

rotation channel. All of these elements would be suitable for a later muon collider. In addition the neutrino factory might include a short muon cooling channel, and would include an acceleration scheme and a storage ring with long straight sections. During Stage 2b the Stage 1 experiments would also be upgraded, or replaced with additional experiments that can exploit the enhancements in the Fermilab facilities. Examples include further muon experiments (for example, a muon electric dipole moment experiment), and further neutrino experiments that complement the low energy neutrino factory. Finally, another important element of Stage 2b is an enhance muon collider R&D program, specifically preparing the way for Stage 3. Stage 2b ends when the community is ready and able to build a multi-TeV muon collider. Budgets and timescales for Stages 2b and 3 are shown in Table 2 and discussed below.

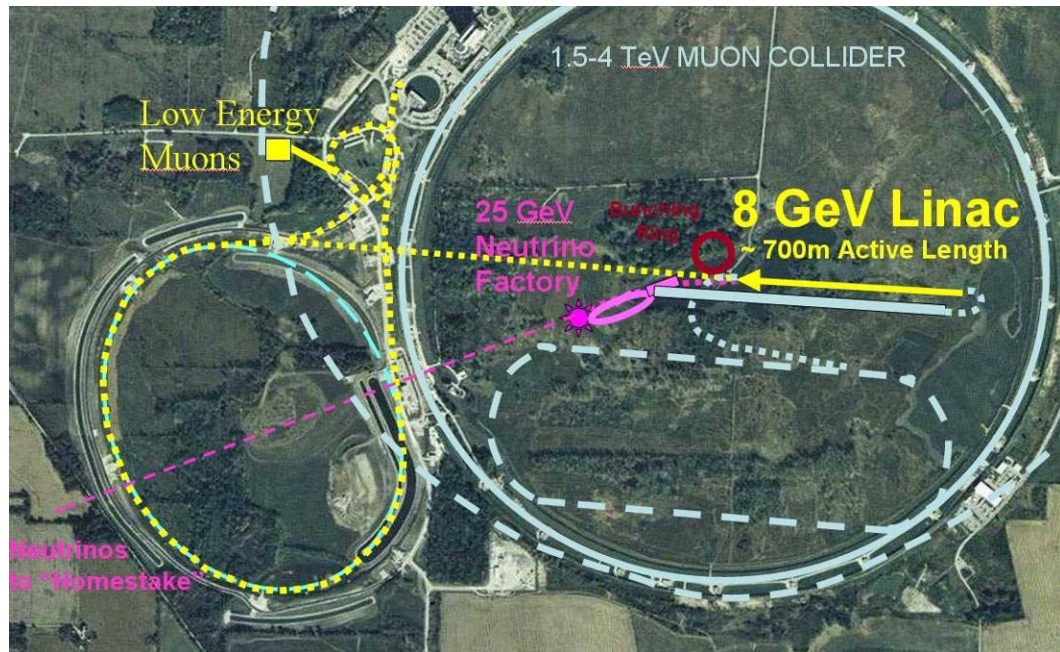


Figure 5: Stage 3 upgrade to a multi-TeV Muon Collider. The accelerator enhancements needed (blue) are a long cooling channel, an acceleration scheme, and a collider ring. The ring is roughly the same size as the Tevatron Collider. In the scheme shown the muons are cooled, and then injected into the proton linac for 1 pass, before being transferred to an RLA followed by a larger circular accelerator. Benefiting from additional cooling and acceleration, the neutrino factory is also upgraded to a higher intensity 25 GeV facility.

Table 2: Very rough fully-loaded budgets (M\$) required to support the construction of Stage 2b and Stage 3 experiments and facilities.

		PROJECT 1: 3000 M\$			BASE PROGRAM EXPERIMENTS			PROJECT 2: 4600 M\$		
		PD+NF	PD Det 1	NF Det 1	PD Det 2	PD Det 3	MC R&D	NF Det 2 + Upgrade	MC	MC Det
YEAR	Sub Tot	2300	200	500	200	200	380	600	3000 (?)	1000
9	210	150	40	0			20			
10	380	300	60	0			20			
11	770	580	70	100			20			
12	800	600	30	150			20			
13	700	460	PD 1	150	40		50			
14	420	210	PD 1	100	60		50			
15	300		PD 1	NF 1	50	50	100	100	0	0
16	350		PD 1	NF 1	50	50	100	150	0	0
17	570			NF 1	PD 2	70		150	300	50
18	800			NF 1	PD 2	30		150	520	100
19	800			NF 1	PD 2	PD 3		50	600	150
20	800				PD 2	PD 3		NF 2	500	300
21	800					PD 3		NF 2	600	200
22	680					PD 3		NF 2	480	200
23						PD 3		NF 2		MC 1

2.4 Stage 3

The main element of Stage 3 is a multi-TeV Muon Collider (Fig. 5). The front-end of the 4 GeV neutrino factory is used together with a long ionization cooling channel, and a scheme that accelerates the muons to about 1 TeV (e.g. 1.5 TeV for a 3 TeV muon collider). The acceleration scheme might utilize the proton accelerator to accelerate the muons to a few GeV, and then perhaps two more acceleration stages to accelerate the muons to TeV energies. The collider ring would be about the size of the present Tevatron Collider. An optional extra for Stage 3 would be an upgrade of the 4 GeV neutrino factory to a high intensity 25 GeV neutrino factory, exploiting the early part of the cooling channel and accelerators being implemented for the muon collider. Finally, a continuing low energy muon program might also be attractive and cost effective during Stage 3.

2.5 Budgets and Timescales

Guesstimated budgets and timescales are shown in Table 2 for Stages 2b and 3.

Project 1 is the Stage 2b construction project which, in this illustration, starts in year 9 (after 8 years of Stage 1). Over a period of 6 years the 8 GeV Proton Driver and 4 GeV Neutrino Factory are built, together with one substantial detector for each. The costs estimates are not very precise, but in the table 1000M\$ + 200M\$ is allocated for the 2 MW Proton Driver + detector, and 1300M\$ + 500M\$ for the Neutrino Factory + detector. The Neutrino Factory costs have been scaled from previous reasonably detailed studies for a 20 GeV Neutrino Factory, taking into account expectations for savings associated with less acceleration, and possibly no (or very little) muon cooling. The total Stage 2b project cost in this example is 3000M\$. Although very substantial, it is perhaps of the same order as the anticipated domestic contribution to an International Linear Collider, and it is therefore plausible that Stage 2b is matched to domestic budgets.

Project 2 is the upgrade from Neutrino Factory to Muon Collider. At present the cost for this is unknown, and all we can do is to use a number which is plausible, but certainly not defensible. The additional facilities required for a muon collider could also be used in part for an upgraded neutrino factory, which should be considered an attractive option rather than a necessity. It seems likely that Stage 3 is more costly than Stage 2b, but perhaps not too much more costly, and again it is not obvious that Stage 3 would not fit within a domestic program.

In addition to the two big projects, Table 2 shows continued support for construction of experiments, and a ramping up of the muon collider R&D, in the “base program”. This enables a continued trend of one new experiment every couple of years, providing some robustness against timescales that stretch out. Note that the first Muon Collider experiment begins data taking in year 23, and for the entire 23 years a diverse accelerator-based program is maintained with a new experiment every couple of years.

3. Summary

We have described a long-term vision for the accelerator-based program at Fermilab that leads back to the energy frontier while

respecting the number one priority (getting the ILC on the fast track). The vision is robust against uncertainties in the timescales for critical ILC decisions and implementation (Stage 1 \rightarrow extended Stage 1). It is also robust against uncertainties in the ultimate fate of the ILC (Stage 1 \rightarrow Stage 2a or 2b). In our vision, every stage preserves a diverse World-class accelerator-based program with new experiments every couple of years. If the path leads through Stage 2b there would be a large pre-Muon-Collider project, consisting of a Proton Driver and low energy Neutrino Factory, that would prepare the way for a multi-TeV Muon Collider. It is plausible that with this staging each project is matched to realizable domestic budgets.